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U.S. ARMY HELICOPTER DRIVE SYSTEM OVERHAUL MANAGEMENT

ORIGINAL

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November 1978

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This technical note presents the findings of work conducted at or for the Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), to determine the feasibility, capability, and impact of operating Army helicopter transmissions without the necessity for mandatory scheduled overhaul periods. Such a policy has commonly been referred to as "on-condition" maintenance.

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TABLE OF CONTENTS

	Page
INTRODUCTION	5
Potential Payoff	5
Definition of Terms	5
Misconception Concerning Drive System Overhaul Management (Percent Reaching TBO)	10
Previous Work Concerning TBO Growth/Extension	10
SCOPE OF INVESTIGATIONS AND ANALYSES	12
Boeing Vertol Company	12
Bell Helicopter Company	13
Sikorsky Aircraft	14
RESULTS OF ANALYSES	16
Boeing Vertol Company	16
Bell Helicopter Company	19
Sikorsky Aircraft	21
CONSIDERATIONS NOT PREVIOUSLY ADDRESSED AND THEIR PROBABLE IMPACT	22
Maintaining Steady Depot Workloads	22
Incorporation of Modification Work Orders (MWO)	22
Potential Failure Modes	23
CURRENT OVERHAUL PROCEDURES	25
Sikorsky Aircraft	25
Boeing Vertol Company	27
Bell Helicopter Company	28
Corpus Christi Army Depot	28
Overhaul Techniques and Procedures for On-Condition Maintenance	29
CONCLUSIONS	30
Composite Conclusions of Boeing Vertol Company, Bell Helicopter Company, and Sikorsky Aircraft	30
General Conclusions	31
RECOMMENDATIONS	33
Currently Fielded and Future Army Aircraft	33
Further Study	33

LIST OF ILLUSTRATIONS

Figure		Page
1	Typical distributions of times to failure	8
2	Typical distribution functions	8
3	Typical reliability functions	9
4	Typical increasing hazard function	9
5	Reliability function for a constant hazard rate	11
6	Typical decreasing hazard function	11
7	Summary of on-condition concepts	18
8	Representative hazard functions of helicopter drive systems	20
9	Sikorsky Aircraft transmission overhaul process	26

INTRODUCTION

This report presents the findings of work conducted at or for the Applied Technology Laboratory, U. S. Army Research and Technology Laboratories (AVRADCOM), to determine the feasibility, capability, and impact of operating Army helicopter transmissions without the necessity for mandatory scheduled overhaul periods. Such a policy has commonly been referred to as "on-condition" maintenance. The phrase "on-condition" may be misleading in that it implies that condition monitoring devices are needed. The impact of those devices is discussed in the Results of Analyses and Potential Failure Modes sections, below.

POTENTIAL PAYOFF

Elimination of designated overhaul intervals is the area that offers the greatest potential payoff in achieving significantly higher replacement times. This contention is supported by the data presented in Table 1, which shows current helicopter transmission removal experience for the UH-1/AH-1 aircraft from four different data sources. The values of MTBR (mean-time-between-removals for all causes) can be seen to be approaching the designated overhaul intervals, or time-between-overhauls (TBO), for each type of gearbox. As the MTBR approaches the assigned TBO, it will be necessary to extend or eliminate the TBO to allow for continued growth. Otherwise, perfectly good transmissions will be overhauled when they could continue to operate on-condition. Examination of the MTBUR (mean-time-between-unscheduled-removals) column in Table 1 shows that if scheduled overhauls were eliminated, the mean removal times would generally exceed the assigned TBOs. Certainly the new MTBR would be larger. Unfortunately, the amount that the MTBR would change by eliminating scheduled overhauls is a function of the data source selected. The most optimistic data source shown in Table 1 is the Fort Rucker data, since Fort Rucker has essentially an ideal maintenance environment; i.e., contract maintenance. That data shows substantial potential increases in mean removal times by eliminating scheduled overhauls. However, even the worst improvement projected by these data sources by eliminating scheduled overhauls (the Bell data for the 42-degree and 90-degree transmissions and the Corpus Christi data for the main transmission) shows considerable potential improvement over the MTBR when scheduled overhauls continue to exist.

Unless the TBO is allowed to be extended or eliminated, little or no improvement in transmission MTBRs can be achieved. This report will, consequently, address how and why the TBO can and should be extended or eliminated. Before addressing the issues surrounding TBO extension or elimination, i.e., TBO management, it will be necessary to define some terms and concepts.

DEFINITION OF TERMS

On-condition Maintenance. On-condition maintenance is the practice whereby repair or overhaul is performed only on components exhibiting performance degradation, as opposed

to having all components overhauled at established intervals; i.e., TBOs. The objectives of having established overhaul intervals are the attainment of high aircraft availability by maintenance scheduling; incorporation of modification work orders (improved components or fixes installed to eliminate defective components); maintaining a steady workload at the overhaul facilities; and detection of unanticipated, and otherwise undetectable, failure modes.

Distribution of Times to Failure. Typical distributions of times to failure are shown in Figure 1, where f(t) is called the density function and t is time. The density function is a mathematical equation used to serve as a model for the shape or pattern of variability for a particular group of data.

Distribution Function. The distribution function, or unreliability, F(t) is equal to $\int_0^t f(t)\,dt$. Typical distribution functions are shown in Figure 2. F(t) is also known as the probability of failure.

Reliability Function. The reliability function, R(t), is equal to 1-F(t). Figure 3 shows a typical distribution of R(t). The reliability function is also known as the probability of no failure or, more precisely, the probability of a component performing its function adequately for a specified time under the operating conditions to be encountered.

Hazard Function. The hazard rate, H(t), is the instantaneous failure rate of a component at time t, conditional upon its successfully operating up to time t. The hazard function is equal to F(t) divided by R(t). It describes how the failure rate of a given component changes as its operating time increases. Figure 4 shows a typical hazard function (in this case, increasing with time). It is important to know the shape of the hazard function because it tells how a component can be expected to behave if it has survived to a certain time, such as its designated overhaul interval. If a component exhibits an increasing hazard function, this usually indicates a wear-out phenomenon or deterioration with age. If, on the other hand, a component exhibits a decreasing hazard function, this usually indicates that "infant mortality" may be being experienced. An example of something that could cause infant mortality would be assembly errors. Those types of errors in manufacturing would be more likely to occur during the early stages of a component's operation than later. The hazard rate of a series system at some point in time is the sum of the hazard rates of its components at that point. This relationship is useful in determining the assembly hazard functions from component hazard functions.

Weibull Distribution. A convenient distribution of times to failure useful in TBO management is the Weibull distribution since, depending on the parameters of the distribution, increasing, decreasing, or constant hazard functions can be represented using that distribution. The Weibull distribution is an excellent approximation of many distributions. It can be described by specifying two parameters, a shape parameter (β) and a scale parameter (θ). β is indicative of the manner in which the probability is distributed in relation to time. θ is indicative of the height of the hazard function and is equal to the time at which the cumulative probability of failure is equal to 63 percent.

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TABLE 1. HELICOPTER TRANSMISSION REMOVAL EXPERIENCE

Components and data source	TBO (hours)	Mean-time-between-removals (hours)	Mean-time-between-unscheduled-removals (hours)
UH-1/AH-1 main transmission			
Bell data (Reference 1)	1100	817.5(d)	2023.6(d)
Corpus Christi Army Depot (CCAD) data(a)	1100	835.5(d)	1450.0(d)
Fort Rucker data (b)	1100	746.9(d)	3500.0(d)
AVSCOM data (c)	1100(f)	728.5(e)(f)	2884.8(e)(f)
UH-1/AH-1 42-degree transmission			
Bell data	1500	925.8	1404.8
CCAD data	1500	1106.9	2150.0
Fort Rucker data	1500	1148.0	3800.0
AVSCOM data	1500	1085.7	2276.7
UH-1/AH-1 90-degree transmission			
Bell data	1100	709.7	1175.0
CCAD data	1100	779.0	1600.0
Fort Rucker data	1200	911.3	2800.0
AVSCOM data	1133	794.7	1635.5

(a) CCAD data for period 1 July 1976 - 30 June 1977.

(b) Fort Rucker Component Reliability Report as of 31 December 1977.

(c) UH-1 and AH-1 demand data for 24-month period ending 22 August 1977.

(d) Obtained by using Weibull probability paper to determine θ and β. MTBR = $\Upsilon + \theta \left[1 - e^{-\left(\frac{t-\Upsilon}{\theta}\right)^{\beta}} \right]$ and MTBUR = θ

(e) Assumes $\Upsilon = 0$, $\beta = 1$, θ = MTBUR

(f) There is no way of knowing the TBO for the AVSCOM-returned transmissions/gearboxes. Hence, these TBO intervals are averages of the previous TBO values for the Bell, CCAD, and Fort Rucker data.

[1] Knudsen, G. E., and Keating, J. R., *Helicopter Drive System On-Condition Maintenance Capability (UH-1/AH-1)*, Bell Helicopter Company; USAAMRDL Technical Report 75-52, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A028032, pp. 56-58.

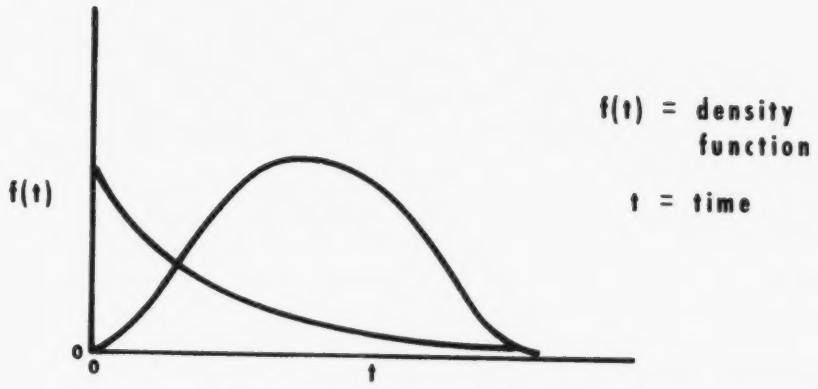

Figure 1. Typical distributions of times to failure.

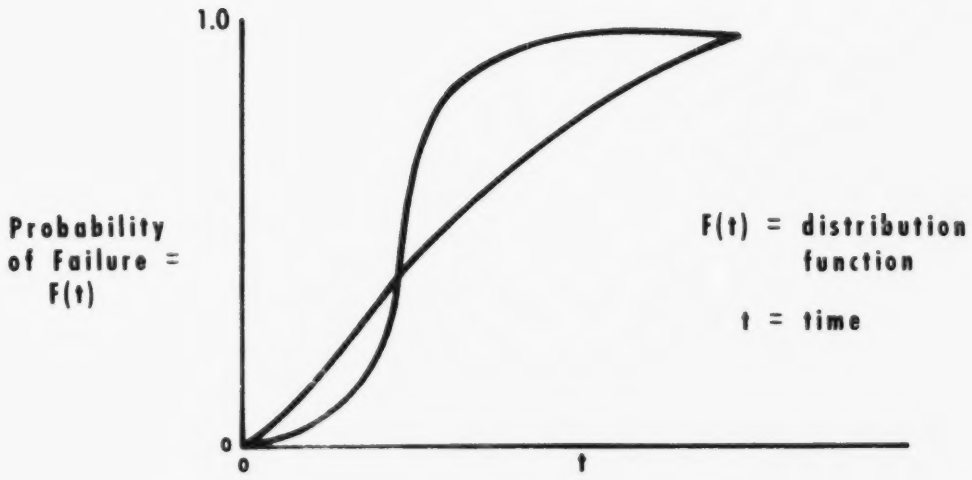

Figure 2. Typical distribution functions.

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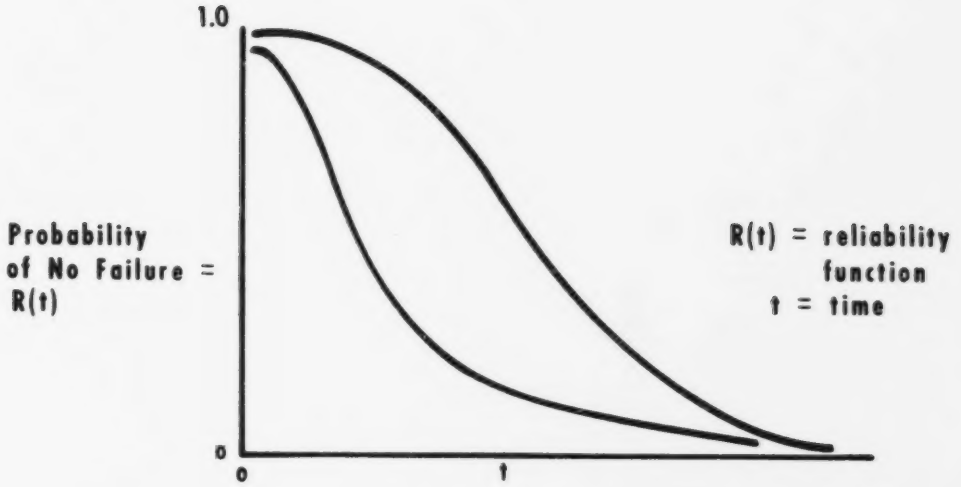

Figure 3. Typical reliability functions.

Figure 4. Typical increasing hazard function.

MISCONCEPTION CONCERNING DRIVE SYSTEM OVERHAUL MANAGEMENT (PERCENT REACHING TBO)

One reason for having a scheduled overhaul interval is to eliminate or, at least, minimize failures occurring that might be prevented by the overhaul process. Another reason is to get a "like-new" or "zero-time" component at a cost appreciably lower than a newly manufactured item. Both of these reasons have meaning only when a component has an increasing hazard function. For components with constant or decreasing hazard functions, overhauling those items will have no effect or will result in a component with a higher failure rate (hazard rate) than before the overhaul. This concept will be discussed in more detail later. For components with increasing hazard functions, overhauling the components should lower the hazard rate, thereby resulting in components with some failure modes eliminated that would have occurred had the components been allowed to operate in excess of the overhaul interval. How and when to extend an established TBO interval is one question that must be answered to adequately address TBO extension and on-condition maintenance. Some of the issues that must be considered before one can answer that question will be discussed in the remainder of this report.

One of the most frequently cited reasons for extending a TBO is a high percentage of components reaching their scheduled overhaul interval. The percent reaching TBO essentially defines one point of the reliability function where the TBO represents time and the percent reaching TBO is an estimate of the reliability. To determine whether or not a TBO is appropriate, the behavior of the hazard function must be investigated. The percent reaching TBO is a mathematical tool which may be used to establish the parameters of the hazard function (see Figure 4). For components that exhibit a constant hazard rate, there is an equal probability of a failure occurring during each unit of time. Consequently, overhauling a component that has not failed does not gain additional operating time for that component. Figure 5 shows graphically that for components that exhibit a constant hazard rate, increasing the TBO from t_1 to t_2 does, in fact, result in a lower percent reaching the scheduled TBO; i.e., R_1 is greater than R_2 where R is roughly equivalent to a percent reaching TBO. Investigation of the hazard function shows that the probability of failure in a small time interval after TBO does not change, given that the component has reached TBO regardless of the actual value of the TBO.

Figure 6 shows a typical decreasing hazard function. It can be seen that the probability of failure would decrease, given that the component had reached its TBO. Since overhauling theoretically returns a component to zero time, overhauling this component increases the hazard rate. Consequently, an overhaul would hurt a component that has a decreasing hazard function.

PREVIOUS WORK CONCERNING TBO GROWTH/EXTENSION

The Applied Technology Laboratory has completed several in-depth analyses of helicopter gearbox TBO assignment and management. Three reports had been published by the Applied Technology Laboratory as of July 1976 which deal with on-condition maintenance of helicopter drive system components. These reports will be discussed in detail in the following sections.

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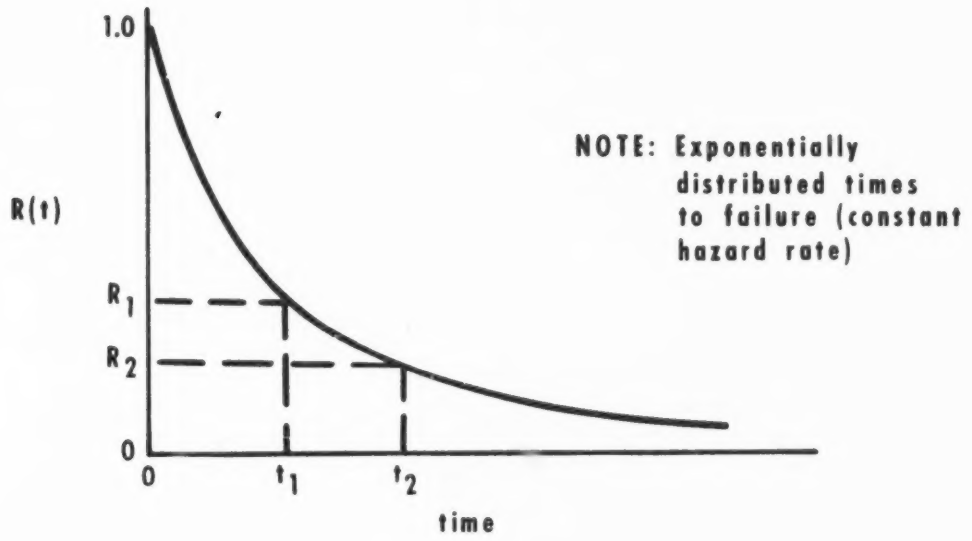

Figure 5. Reliability function for a constant hazard rate.

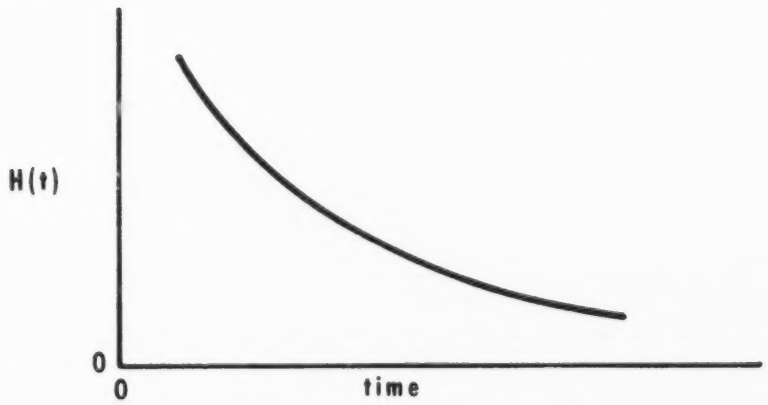

Figure 6. Typical decreasing hazard function.

SCOPE OF INVESTIGATIONS AND ANALYSES

The Applied Technology Laboratory contracted for three separate studies to investigate on-condition maintenance issues for helicopter drive system components. Each of those studies will be summarized below.

BOEING VERTOL COMPANY

The initial task in the on-condition work was performed by the Boeing Vertol Company (BVC) (Reference 2). BVC developed an analysis procedure to determine the capability of transmissions to operate with no TBOs. The technique has been applied to the following transmissions:

a. CH-47C engine transmission

b. CH-47C combining transmission

c. CH-47C forward transmission

d. CH-47C aft transmission

e. CH-46 forward transmission

f. CH-46 aft transmission

g. CH-46 mixing transmission

h. H-3 main transmission

i. UH-1 main transmission

This work and an in-house BVC report (Reference 3) documented the feasibility of on-condition maintenance as a viable alternative to scheduled overhauls and provided general guidelines for more detailed analyses. BVC developed a methodology for examining test and field data from operational components to determine or to establish appropriate TBO levels or the capability for on-condition operation. In addition, they developed design and test criteria that permit determination of the TBO or on-condition capability of components early in the system life cycle. BVC determined that there are at least two

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[2] Dougherty, J. J., III, and Blewitt, S. J., *Analysis of Criteria for On-Condition Maintenance for Helicopter Transmissions*, Boeing Vertol Company; USAAMRDL Technical Report 73-58, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, September 1973, AD 773024.

[3] Dougherty, J. J. III, and Rummel, K. G., *Capability of CH-47C Forward, Aft, and Combining Gearboxes for On-Condition Operation*, Boeing Company Report D210-10367-1, Philadelphia, Pennsylvania, December 1971.

objectives to be considered in the establishment of an on-condition maintenance philosophy. First, the removal of the TBO interval should result in a decrease or, at least, no increase in the number of failures that could possibly cause an accident. Second, the application of the on-condition maintenance philosophy should be cost effective or it should not be accepted; i.e., removal of the TBO interval should result in an increase or, at least, no decrease in cost effectiveness where cost effectiveness is a function of availability, mission reliability, and operating and maintenance costs.

BVC conducted their analysis as described below:

a. Defined concepts and terms such as on-condition, TBO, and hazard function.

b. Evaluated the relationship between the on-condition maintenance philosophy and reliability, maintainability, safety, availability, and cost.

c. Developed methods of quantifying the relations in subsection b above.

d. Collected pertinent transmission maintenance data; reduced and analyzed it.

e. Determined the significance of various failure modes by conducting a failure mode, effects, and criticality analysis (FMECA).

f. Analyzed the impact of redesign, testing, and failure warning and inspection systems on the use of on-condition maintenance.

g. Summarized the pertinent criteria and various considerations one would use in analyzing whether or not to allow helicopter transmissions to be maintained on-condition.

BELL HELICOPTER COMPANY

Bell Helicopter Company (BHC) conducted a study similar to the Boeing Vertol Company's effort except that it addressed the UH-1 and AH-1 series helicopters. The results are reported in Reference 1.

BHC assessed the capability of the following UH-1 and AH-1 helicopter dynamic components to operate with no scheduled overhaul periods:

a. Main transmission

b. Intermediate transmission

c. Tail rotor transmission

d. Main rotor hub

e. Swashplate and support

The general approach used by BHC was to examine the overhaul and accident records, the inspection procedures, and the functional capability of caution and warning subsystems and their condition monitoring devices to determine if there was any failure mode that

limited on-condition maintenance.

Data sources used by BHC included the following:

a. The Army Maintenance Management System (TAMMS), DA Form 2410, copies 1 and 3 through 6.

b. Disaassembly Inspection Summary Records, SAV Form 634, for component overhauls.

c. The U. S. Army Agency for Aviation Safety (USAAVS) accident report records for the UH-1 and AH-1 aircraft.

d. U.S. Army maintenance manuals for the UH-1B/C/D/H and AH-1G aircraft.

e. U.S. Army preventive maintenance checklists for the UH-1B/C/D/H and AH-1G aircraft.

BHC observed that if, after installation, a component is removed prior to operation of its scheduled TBO interval, it is removed essentially "on-condition." Therefore, since an on-condition maintenance capability exists and is, in fact, relied on to ensure safe operation of the drive system components from installation to scheduled overhaul, the BHC approach was to examine how well these methods might assure safe operation of these components if the TBO interval were extended or eliminated.

BHC performed a failure mode and effects analysis (FMEA) on parts selected for their potential criticality and on parts shown to be potentially critical by an accident data analysis (also performed by BHC). If any part was suspected of having a failure mode that could cause an assembly failure or that resulted in an aircraft mishap of a severity equal to or greater than that of a forced landing, the part and its failure mode were included in the FMEA. Examples of such parts include the UH-1 main transmission spur gear, shaft, and oil pump and the UH-1 main rotor hub housing assembly. The data for each aircraft type were sorted by mishap classification and failure/malfunction code and counted to determine the total number of material failures for each aircraft model by mishap classification. Finally, a part or subsystem was analyzed using a FMEA to determine if it could be maintained on-condition.

SIKORSKY AIRCRAFT

Sikorsky Aircraft (SA) conducted a study similar to the Boeing Vertol Company and Bell Helicopter efforts except that it addressed the CH-53 and CH-54 series helicopters (Reference 4). SA analyzed CH-53 and CH-54 transmission systems to formulate a clear position concerning on-condition maintenance for helicopter drive systems and to identify those design concepts and procedures that could significantly enhance that maintenance philosophy. The results of that work are shown in Reference 4. The transmissions studied were:

a. CH-53 nose transmission

[4] Trustee, B., *Helicopter Drive System On-Condition Maintenance Capability*, Sikorsky Aircraft; USAAMRDL Technical Report 75-57, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia, July 1976, AD A028414.

b. CH-53 main transmission

c. CH-53 intermediate transmission

d. CH-53 tail rotor transmission

e. CH-53 accessory transmission

f. CH-54 main transmission

g. CH-54 intermediate transmission

h. CH-54 tail rotor transmission

SA conducted a reliability analysis that established gearbox hazard functions for safety-of-flight failure modes, mission reliability failure modes, and dynamic removal failure modes. The reliability analysis started by defining and categorizing generic device failure modes in terms of their worst possible effect on aircraft performance. The impact of current transmission inspection techniques and diagnostic systems was then evaluated to determine their ability to alleviate the risk associated with the occurrence of a failure mode or to reclassify a failure mode. Hazard functions were then established for each generic device failure mode from either experience data or from various estimation methods when no experience data were available. Finally, all the hazard functions of a particular failure mode category (safety-of-flight, etc.) were combined and the resultant hazard function was plotted.

RESULTS OF ANALYSES

BOEING VERTOL COMPANY (BVC)

The study completed by BVC in September 1973 was the first of three studies done by industry for the Army to analyze criteria for helicopter transmission on-condition maintenance.

The BVC study (Reference 2) concluded the following:

a. If transmissions lack on-condition capability, analysis of test and field data can determine the correct TBO from system effectiveness and cost standpoints.

b. A method of analysis is available to identify the capability of helicopter transmissions for on-condition operation. That method gives the user a means to evaluate the potential for discontinuing scheduled overhauls without sacrificing safety and effectiveness or to establish a TBO interval at a level that would be most effective. The method is composed of seven steps:

(1) Perform a FMECA.

(2) Develop hazard functions by mode and combine into an assembly hazard function.

(3) Perform a safety evaluation.

(4) Develop a limiting cost-effectiveness hazard function (represents the point beyond which operating on-condition becomes more costly and less effective than operating with a TBO).

(5) Determine optimum cost-effectiveness TBO or substantiate on-condition potential from the cost-effectiveness hazard function.

(6) If on-condition operation is not safe or cost effective, consider the impact of redesign, testing, and failure warning and inspection systems.

(7) Substantiate on-condition or finalize establishment of TBO.

c. When on-condition operation has not been substantiated from both the safety and cost-effectiveness aspects, three courses of action are available if the user still desires to eliminate scheduled removals:

(1) Certain components of the drive system with restrictive hazard functions can be redesigned to eliminate adverse failure modes or to change the hazard functions.

(2) The drive system can be manufactured and tested to minimize infant mortality failure modes in the field. The information from these tests, or green runs, may lead to the insight required for design elimination of those failure modes.

(3) In the case where on-condition operation is unsafe or not system effective, the installation of condition monitoring devices and careful maintenance inspections to provide ample time for safe action or efficient drive system removal should be considered.

d. The entire on-condition question really reduces to a safety issue.

e. Although the concept of operating on-condition is new, it is not untested since all components now operate on-condition to some extent.

Boeing Vertol Company also presented a discussion of various on-condition maintenance concepts and concluded that any decision to implement on-condition maintenance must be based on considerations of cost, mission effectiveness, and safety (Reference 2, pp. 14-15).

Each transmission has three distinct hazard functions: maintenance malfunction, mission abort, and safety. The reduction of each of these hazard functions will produce cost and man-hour savings and is therefore a goal for improved operations and maintenance of the Army's aircraft. The maintenance malfunction hazard rate can be reduced by eliminating unnecessary removals, the mission abort hazard rate can be reduced by improving ground maintenance detection of actual or incipient mission-affecting failures, and the flight safety hazard rate can be reduced by providing sufficient pilot warning for accident avoidance. If a TBO has been established, then those hazard functions will be repeated. If the hazard function is such that it was decreasing until the overhaul occurred, then the hazard rate will instantaneously increase following the overhaul and then decrease until the next overhaul. Figures 7(a) and (b) show this graphically. This increase in the hazard rate should occur because, at least in theory, the item overhauled has been restored to a new, or like-new, condition and should correspondingly experience burn-in failures. Assuming that the item under investigation has an established TBO, an average hazard rate for each hazard function can be calculated (see Figures 7(c) and (d)). A subjective assessment of an item's life-cycle cost is shown in Figure 7(e). It is apparent that scheduled removals at TBO generate cost spikes.

Elimination of scheduled overhauls, i.e., operating on-condition, lets the hazard functions continue in a predictable manner (see Figure 7(f)). Use of failure warning and inspection systems generally reduces all three hazard functions uniformly; however, the specific role of those systems, when used in conjunction with on-condition maintenance, is to eliminate or reduce critical increasing hazard function modes (see Figures 7(g) and (h)). Consequently, use of condition monitoring devices and maintenance inspections in conjunction with on-condition maintenance should reduce the on-condition hazard functions below the average line of the hazard functions with TBOs established.

As Figure 7(i) shows, the maintenance malfunction on-condition hazard function line generally remained above the maintenance malfunction hazard function line of TBO-controlled transmissions. Although that might be true, on-condition maintenance is more cost effective than using a TBO-dominated maintenance concept due to smoothing of the cost spikes introduced by the scheduled overhauls (see Figure 7(j)).

BVC conducted an assessment of the relationship between reliability, hazard function, and on-condition maintenance which is worth reiterating here. The hazard function was defined earlier as the term used to describe how the failure rate of a given component changes as its operating time increases. BVC's discussion of the hazard function states that the

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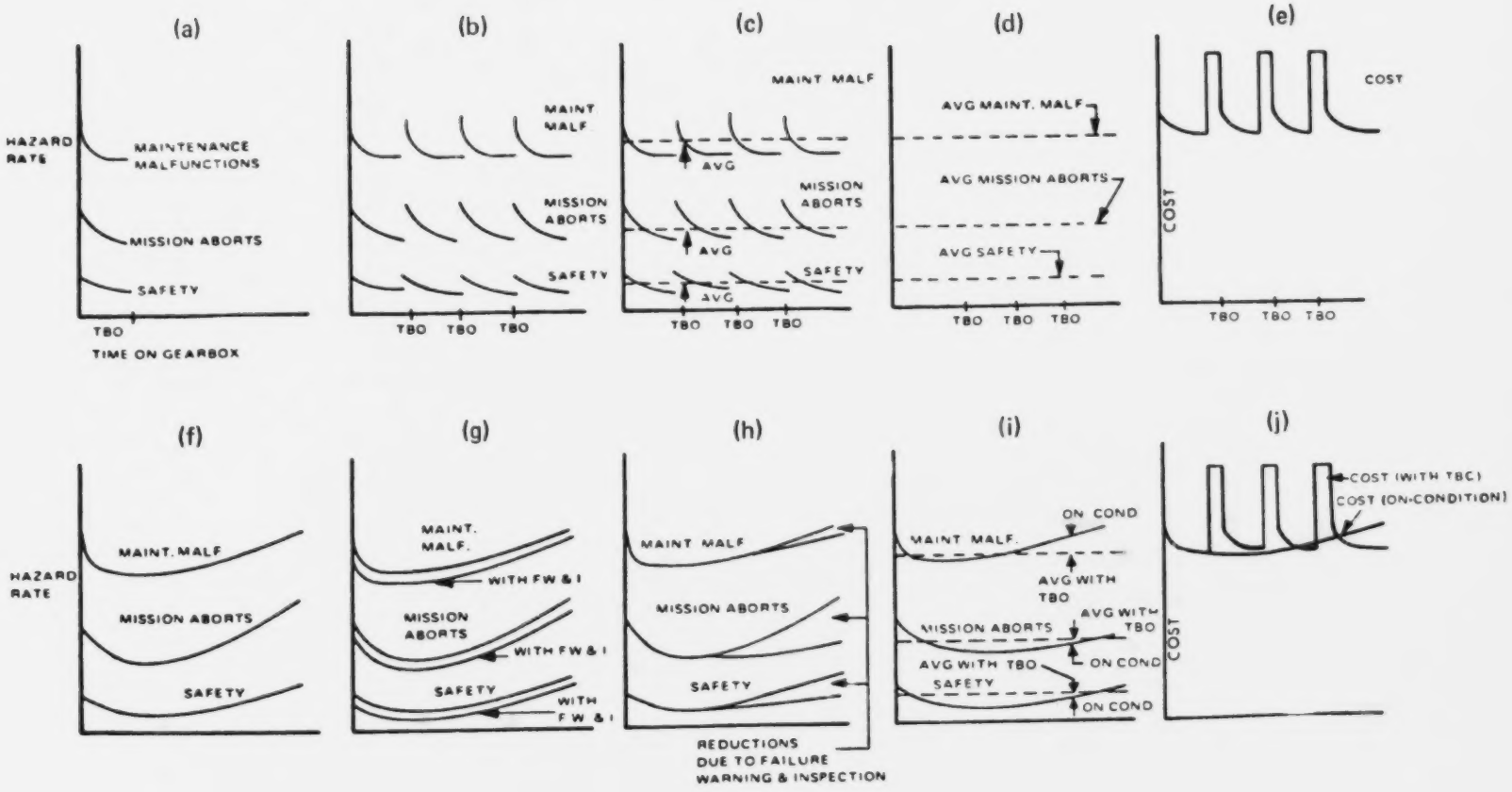

Figure 7. Summary of on-condition concepts.

three hazard functions illustrated (in Figure 8) could each be used to determine a different, but proper, location for the placement of a TBO interval, depending on the desired objectives. On the surface, it would seem to be a simple matter to decide at which point the TBO interval should be established; that is, removals should take place at the point where the failure rate begins to increase. However, after safety considerations have been made, it is essential to determine whether or not removing and repairing the components which could fail due to the increasing hazard rate will be more or less expensive than overhauling all the components of the particular subsystem at a certain interval. Therefore, the hazard function is integral to any process involving a TBO versus on-condition decision.

BVC concluded that the two-parameter Weibull distribution was the most useful descriptor of failure data and that it should be used to describe component failures (Reference 2, p. 8). The Weibull distribution has been defined previously. BVC also concluded that components having hazard functions of the form of decreasing, constant, and decreasing/constant hazard rates are excellent candidates for on-condition operation. The location or isolation of an optimal TBO for those components/subsystems that exhibit an increasing hazard function would involve an optimization process developed by BVC (Reference 2, pp. 69-72 and 206-225).

As noted earlier, BVC concluded that the entire on-condition question really reduces to a safety issue. For those few failure modes that offer a potential safety problem and that exhibit increasing hazard functions, the existing diagnostic techniques and condition monitoring devices are adequate to reduce those problems to maintenance or misssion-affecting ones rather than safety problems.

BELL HELICOPTER COMPANY (BHC)

The BHC report (Reference 1) concluded the following:

a. The system level modes of degradation of performance occur concurrently and proceed until either one of the modes becomes unacceptable or the TBO interval has been reached, at which time the system is removed for overhaul. The system, in this case, is one of the five components analyzed by BHC and identified in the Scope of Investigations and Analysis section. The unacceptable level of degradation would occur prior to any of the modes causing a loss in function. The failure mode and effects analyses of the systems revealed that no modes exist that could degrade system function to an unsafe condition without producing symptions which would be adequate to provide for a failure warning and caution systems detection of the degradation, in sufficient time for safe replacement of the system (Reference 1, p. 38).

b. There is a good probability that the drive system parts will survive more than two assembly overhaul intervals of 1,100 hours.

c. The failure mode and effects analysis showed that no UH-1/AH-1 drive system part has a failure mode that would limit an on-condition maintenance capability. It also indicated that no part of any UH-1/AH-1 drive system assembly has a failure mode that would impair flight safety that would not be precluded by degradation adequate enough to be observed either by inspection processes or by the caution and warning systems.

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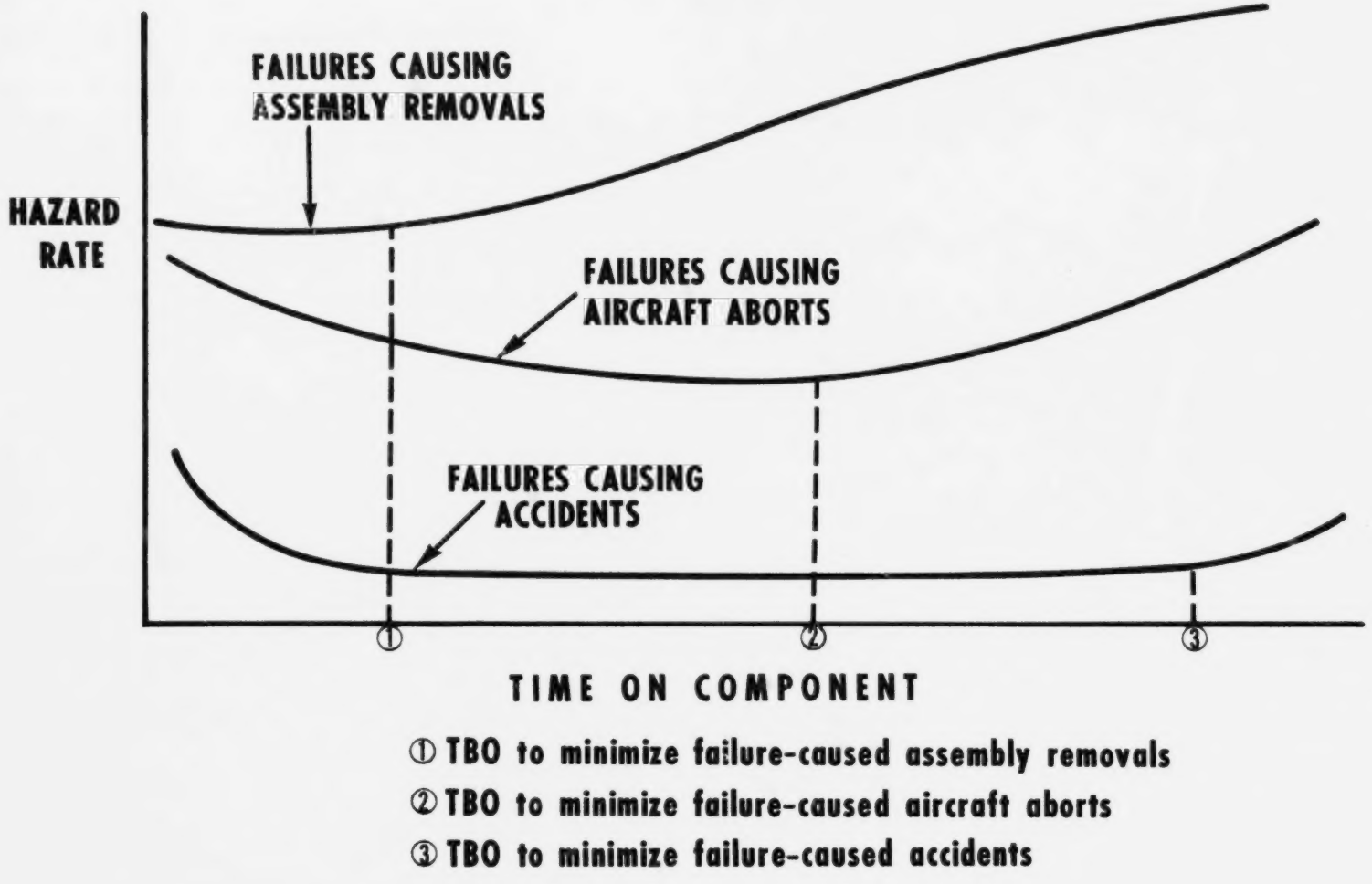

Figure 8. Representative hazard functions of helicopter drive systems.

d. The five drive system components' failure distributions studied by BHC each exhibited an approximate constant failure rate.

e. An on-condition maintenance capability should be limited to the retirement time on the life-limited parts.

f. BHC recommended that a study be performed to establish guidelines to plan and schedule spare assemblies and parts replacement for components overhauled and/or repaired on-condition.

SIKORSKY AIRCRAFT (SA)

The Sikorsky Aircraft (SA) report (Reference 4) concluded the following:

a. With only minor modifications, the transmissions studied are suitable for on-condition maintenance.

b. The current maintenance inspection techniques and condition monitoring and diagnostic devices are adequate to detect flight safety and mission abort related failure modes. There will be no significant increase in potential flight safety malfunctions by going to on-condition maintenance, nor will there be any significant decrease in mission reliability or increase in transmission removals for Sikorsky designed and built transmissions.

c. Life-limited components of the CH-53/54 transmissions will not prevent the establishment of an on-condition maintenance program for those components.

d. Once the transmissions are maintained on-condition, they should be monitored to verify the projections of the hazard functions as well as to keep abreast of any unforeseen problem areas.

e. The fact that only a limited number of improvements are recommended by Sikorsky as necessary to go to on-condition maintenance reflects the fact that Sikorsky's transmission reliability is governed by few catastrophic failure modes; i.e., safety-related modes.

f. If on-condition maintenance is initiated, it is recommended that a data collection program for drive systems be instituted.

CONSIDERATIONS NOT PREVIOUSLY ADDRESSED AND THEIR PROBABLE IMPACT

MAINTAINING STEADY DEPOT WORKLOADS

The issue of maintaining steady depot workloads has not been previously addressed and is of concern with the implementation of any new maintenance system. The current system of established TBOs allows the depots to plan for a certain workload dependent on fleet size and the number of items requiring overhaul prior to their scheduled overhaul interval. Those items requiring overhaul prior to their scheduled interval do so because they reach some unacceptable performance level and are, in essence, already operating under an on-condition maintenance philosophy. Hence, the only portion of the depot's workload that would be altered by going to an on-condition maintenance concept would be that portion that is attributable to components reaching their scheduled overhaul interval. Typically, UH-1/AH-1 gearboxes have shown that between 17 and 24 percent reach their assigned TBO and are removed (Reference 1, pp. 74-84). Consequently, approximately three-fourths of the UH-1/AH-1 gearboxes currently removed are operating on-condition. The scheduled removal of the gearboxes from the field does increase the workload at depot, and conversely, elimination of scheduled overhauls will decrease depot workload. However, for a constant hazard rate, the workload may be steady. The drive system components considered by Bell Helicopter Company (Reference 1, p. 50) exhibited a constant hazard rate, whereas those components considered by Boeing Vertol Company (Reference 2, p. 40) exhibited a decreasing hazard rate. For decreasing hazard rates, the total workload should be decreasing with time, whereas increasing hazard rates would cause an increasing workload, not considering the impact of introducing new components into the inventory. Determination of whether or not on-condition operation provides a maintainability benefit for those components having increasing or decreasing hazard functions will have to be made on a case-by-case basis. Maintainability benefit in this case refers to how the depot workload is affected.

As noted in the Results of Analysis section, the planning and scheduling of spare assemblies and replacement parts for components overhauled on-condition is a difficult logistics problem. How to provision the depots to minimize delays in the overhaul process must be considered before on-condition maintenance can be accepted as a viable maintenance philosophy.

INCORPORATION OF MODIFICATION WORK ORDERS (MWO)

Another issue that has to be assessed before instituting on-condition maintenance of components of helicopter drive systems is how to incorporate MWOs. Currently, some MWOs are incorporated in the field by direct or general support, by the organization if simple enough, or at the depot during overhaul or as part of the Inspect and Repair Only as Needed (IROAN) process. If scheduled overhauls are eliminated, those MWOs that would be accomplished during the overhaul may have to be accomplished some other way. Consequently, the workload will increase at the other maintenance levels to carry out incorporation of MWOs or the installation of the MWOs will be delayed until an overhaul

is necessary. A study should be performed to assess how best to carry out the incorporation of MWOs if scheduled overhauls are eliminated for helicopter drive system components. Whether or not an on-condition maintenance philosophy is adopted, any incorporated MWO should not cause a safety-of-flight problem or life-limit previously unlimited parts. An MWO thus incorporated would, at the very least, negate on-condition maintenance for that system. Life-limited components are those components with definite retirement times rather than those with increasing hazard functions.

POTENTIAL FAILURE MODES

To isolate potentially catastrophic failure modes, it is necessary that a FMECA be performed for the components under consideration for on-condition maintenance. Failure modes having a potentially catastrophic failure progression or modes having an increasing hazard rate during the expected life of the component should be examined very carefully (Reference 2, p. 112). It is the contention of Sikorsky Aircraft Division that most failure modes which could affect a decision concerning whether or not to go to on-condition maintenance are currently known (Reference 4, p. 91). The reason that the word "most" was used is that there are two types of failure modes that may affect a decision concerning whether or not to adopt on-condition maintenance. The two types of failure modes are those that are not detected by current maintenance inspections, diagnostic techniques, or condition monitoring devices and those modes that have a significant potential to affect the safety-of-flight of the aircraft. Those failure modes identified by Sikorsky that are not detected by current diagnostic techniques and condition monitoring devices exhibit a constant hazard function. Hence, those modes should not preclude one from making a decision about whether or not to go to on-condition maintenance; i.e., items that exhibit constant hazard functions may gain nothing from a scheduled overhaul interval. Components that contain only constant and/or decreasing hazard functions are excellent candidates for on-condition maintenance. On the other hand, components that contain increasing hazard functions are not good candidates for on-condition maintenance since there is an apparent advantage to be gained by overhauling the item and returning that item to a "zero-time" or "like-new" condition; i.e., to a lower hazard rate. A trade-off may be necessary between cost and replacement rate in selecting the overhaul interval (TBO) to optimize the resulting hazard rate. However, as noted earlier, potential safety-of-flight-affecting failure modes have exhibited a constant hazard rate and are, hence, not prohibitive in deciding whether or not to go to on-condition maintenance. Similarly, a lack of adequate maintenance inspections and condition monitoring devices will not preclude going to on-condition maintenance.

One area of concern with respect to potential failure modes is when the wear-out mode of degradation begins to exceed the component's fatigue life as aircraft are designed to carry heavier loads and fly faster, further, higher, and longer. Care must be exercised to insure that fail-safe characteristics are not compromised by the introduction of on-condition maintenance; i.e., insure that the fail-safe characteristics are within the limits of the expected operating loads to minimize the possibility of unknown failure modes occurring. As noted earlier, of those modes that could cause potential safety-of-flight problems as a result of instituting on-condition maintenance, current diagnostic techniques and condition monitoring devices can be employed to reduce their impact to mission- or maintenance-affecting modes (Reference 2, p. 40).

As new aircraft systems are introduced into the inventory and as current inventory aircraft are uprated, it would be good procedure to designate certain units as "lead" units to be carefully monitored to assess the impact of those aircraft being maintained on-condition or with extended TBOs. The increased forces imposed on uprated or new technology aircraft introduced into the fleet may affect the fatigue life to such an extent that wear phenomenona will not be displayed before fatigue failures occur. While current diagnostic techniques may be sufficient to reduce safety-affecting failure modes to mission- or maintenance-affecting modes, there is enough doubt to warrant a conservative approach in instituting on-condition maintenance. Therefore, a rapid TBO growth program using designated "lead-the-fleet" units should be considered for implementation of on-condition maintenance, using periodic analytical teardown of the components being assessed to provide data for growth justification.

CURRENT OVERHAUL PROCEDURES

To insure that adequate consideration is given to components that are returned to the field from a depot following overhaul, it is necessary to understand how the overhaul of Army aircraft drive system components is conducted at each of the primary overhaul facilities: Sikorsky Aircraft, Boeing Vertol Company, Bell Helicopter Company, and Corpus Christi Army Depot. This understanding is necessary because to properly assess the impact of instituting on-condition maintenance, it is necessary to know the total hours accumulated on each component to determine the remaining life of that component. This, in turn, is necessary to know to make sure that parts are not used beyond their fatigue lives.

One way of keeping track of operating time on drive system components is by using the aircraft's log and by insuring that the component is reassembled following overhaul using the same parts it originally had (gears, housing, etc.) plus replacement items found to be necessary at overhaul such as bearings and seals. In this way, the total operating time of the components can be determined and tracked.

The Sikorsky Aircraft overhaul process will be discussed first.

SIKORSKY AIRCRAFT

Figure 9 shows graphically the overhaul process used by Sikorsky Aircraft to overhaul their gearboxes. In brief, a gearbox is subjected to the following when overhauled:

a. Incoming inspection: The condition of the shipping container and the outside of the transmission is noted for possible handling damage, corrosion, etc., and assigned a control number.

b. Teardown: The transmission is completely disassembled with the parts being placed on a series of carts. In general, the parts of a transmission flow through the overhaul process together and are identifiable as to the transmission from which they are removed. There is some mixing of parts that are not life limited and belong to the same customer. The life-limited parts are not removed unless they have reached their life limit.

c. Cleaning: The parts are placed in various cleaning solutions in this stage of the process.

d. Evaluation: The parts are subjected to various evaluations such as magnaflux (ferrous parts), zyglow (nonferrous parts), and visual and dimensional inspections, as appropriate. The result of the evaluation is noted on an inspection sheet and is retained for future reference.

e. Reassembly: The transmission is reassembled with parts from the carts noted above that have successfully passed inspection, new parts, and reworked parts.

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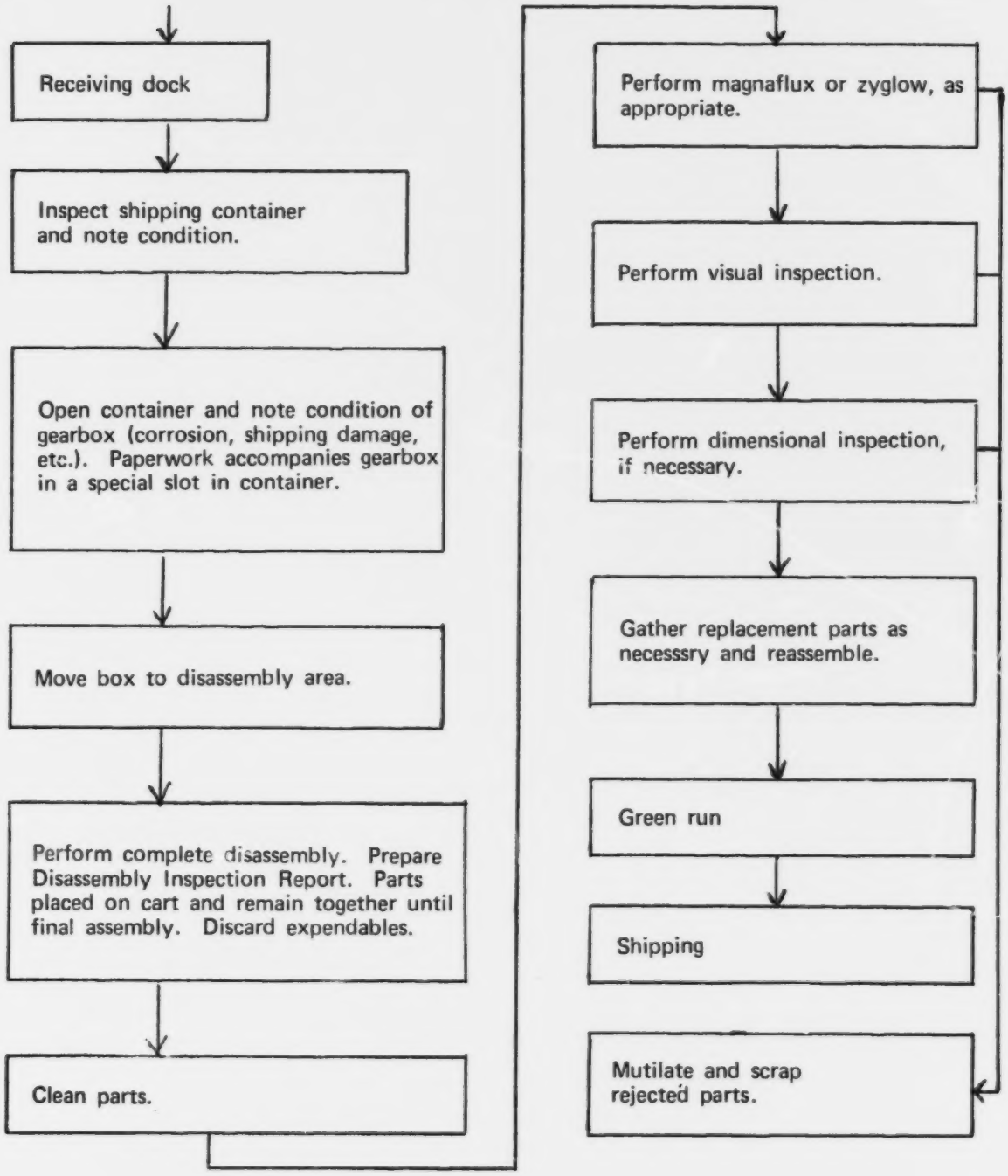
Receiving dock
Inspect shipping container and note condition.
Open container and note condition of gearbox (corrosion, shipping damage, etc.). Paperwork accompanies gearbox in a special slot in container.
Move box to disassembly area.
Perform complete disassembly. Prepare Disassembly Inspection Report. Parts placed on cart and remain together until final assembly. Discard expendables.
Clean parts.
Perform magnaflux or zyglow, as appropriate.
Perform visual inspection.
Perform dimensional inspection, if necessary.
Gather replacement parts as necesssry and reassemble.
Green run
Shipping
Mutilate and scrap rejected parts.

Figure 9. Sikorsky Aircraft transmission overhaul process.

f. Green run: The assembled transmission is run under no load to confirm that parts are reassembled properly and that the lubrication system is functioning adequately.

The inspection philosophy for gears and bearings during overhaul at Sikorsky is as follows:

a. No sophisticated gear tooth profile checks are performed on the basis that gears reaching overhaul have already been accepted by the production quality control system and that any abnormal wear will manifest itself clearly on the tooth and will be visually detectable. Gears do not exhibit smooth, even wear according to Sikorsky Aircraft. Instead they either crack or spall and, hence, require only a visual inspection.

b. All dynamic surfaces of bearings are inspected after cleaning. In some bearings this is a relatively simple task, while in others it may require the inspector to painstakingly rotate a gap in a phenolic spacer to inspect the outer race of a bearing. Little faith is placed in determining the condition of a bearing by "feel." Most of Sikorsky's transmission bearings are reinstalled.

BOEING VERTOL COMPANY

The overhaul procedures followed by Boeing Vertol are generally similar to those employed by Sikorsky with the following exceptions:

a. Teardown: The transmission is completely disassembled with the parts sorted as to type. Little information is collected at this stage of disassembly concerning possible failure modes of transmissions removed for cause. After this stage of the overhaul process, the transmission is no longer identified as a unit.

b. Reassembly: When a requirement for transmission arises, the necessary parts are drawn from the parts storage area and reassembled.

The inspection philosophy for gears and bearings during overhaul at Boeing Vertol Company is as follows:

a. Gears receive a visual check. No sophisticated gear tooth profile checks are performed on the philosophy that gears reaching overhaul had previously been accepted by rigorous production quality control tests and that any abnormal deterioration of the tooth profile would manifest itself clearly and would be visually detectable.

b. The evaluation of bearings appears to be a very subjective one with very little quantitative inspection criteria. A visual check is performed on the dynamic surfaces where possible. The inspector depends heavily on "feel" in making the final determination on the acceptability of the bearing.

Upon successful completion of the evaluation, parts are preserved and placed in parts storage areas. Discrepant parts are either scrapped or reworked, depending on the nature and severity of the discrepancy.

BELL HELICOPTER COMPANY

The overhaul procedures followed by Bell Helicopter Company are generally similar to those employed by Sikorsky with the following exceptions:

a. The Bell Helicopter Company transmissions overhaul facility shares the facilities and equipment of the transmission production line. The current workload for military overhauls is on the order of four transmissions per week. The same general steps noted for Sikorsky are carried out at Bell. Bell transmissions have no life-limited components. However, Bell has "critical" parts which must be carefully inspected or are designated as mandatory replacement parts, but no attempt is made to determine or record their condition upon disassembly. All critical parts carry a serial number. Mandatory replacement parts are parts that must be replaced if a transmission is overhauled. Life-limited parts cause a transmission to be pulled for replacement of those parts or for an overhaul.

b. Teardown: Very little data is collected at time of disassembly unless there is a specific request to do so. The Disassembly Inspect Summary Report contains the evaluator's findings for parts that undergo evaluation. The fact that certain critical parts require mandatory replacement at every overhaul and that data is not routinely collected for those parts limits the data that may be essential in making a TBO extension decision. The practice of discarding those parts obviates the necessity for keeping track of the time on those parts but results in a serious gap in the data.

c. Evaluation: Currently, Army aircraft transmission parts remain together through the overhaul process but only because the volume of overhaul work is very low. When large numbers of transmissions were overhauled at Bell, parts were mixed. Commercial transmissions are always kept together. Aside from the zyglow and magnaflux inspections, which require special equipment, a transmission is evaluated by an inspector.

d. Reassembly. When a requirement for a transmission arises, parts that successfully pass the evaluation along with new replacement parts are reassembled, subjected to a full load green run, partially disassembled for inspection, and reassembled.

The inspection philosophy for gears and bearings during overhaul at Bell Helicopter Company is as follows:

a. Gears are inspected visually. Dimensional checks are not required but may be performed at the request of the inspector. The rationale is that since critical areas are coated, wear in those areas is visually detectable by the absence of the coating.

b. Bearings are inspected both visually and by "feel."

CORPUS CHRISTI ARMY DEPOT

The overhaul procedures followed by the Corpus Christi Army Depot (CCAD) are generally similar to those employed by Sikorsky with the following exceptions:

a. Teardown: Very little data is collected at the time of teardown to determine failure modes unless there is a specific request to do so. After teardown, parts are segregated according to type. Parts removed from a transmission do not remain together

through the overhaul process unless they are part of a set, such as a duplex or triplex bearing set or a critical assembly such as planetary post stiffening plates. Gears do not remain together as gear sets.

b. Evaluation: Rejected parts are usually scrapped unless their value exceeds $200, in which case they are set aside for further review to determine whether they can be salvaged or reworked. This decision is made by an engineer from the AVRADCOM Engineering Support Branch. He may authorize deviation from the overhaul specifications.

c. Reassembly: Parts that successfully pass the evaluation are stored and subsequently drawn from the storage area for reassembly.

The inspection philosophy for gears and bearings during overhaul at CCAD is as follows:

a. The evaluation of gears is strictly a visual one. The rationale for this is that the gears were originally accepted prior to installation in a transmission and that any deterioration in the tooth profile would be visually detectable.

b. Most inspections are performed on bearings both visually and by "feel," although the capability does exist to spin-up bearings. Evaluation results are recorded for the batch of bearings being processed and not for individual bearings unless the bearings are identified as being critical or life limited.

At CCAD, no attempt is made to determine the condition of life-limited parts. However, a tag goes out with each gearbox overhauled showing the time-since-new on its life-limited parts. In addition, some life-limited parts such as bearings get their time-since-new up to that overhaul etched directly on them.

OVERHAUL TECHNIQUES AND PROCEDURES FOR ON-CONDITION MAINTENANCE

As the previous discussion shows, there are enough differences between the way the different prime helicopter manufacturers overhaul transmissions that these differences should be taken into account if one wants to initiate on-condition maintenance or to institute a rapid TBO growth program. When the transmission includes life-limited components and must be sent back to a depot to be overhauled under an on-condition maintenance philosophy, it will be necessary that the time-since-new of each life-limited part be known. This information must be known since some of those parts may have to be replaced; i.e., they have reached their life limit or have failed. In addition, a maintenance scheme should be considered when using a maintenance program based on on-condition maintenance that would allow replacement of life-limited parts in the field. This would allow repair at the lowest possible maintenance level.

CONCLUSIONS

COMPOSITE CONCLUSIONS OF BOEING VERTOL COMPANY, BELL HELICOPTER COMPANY, AND SIKORSKY AIRCRAFT

The following conclusions are based on the analysis of data presented or referenced in this report:

a. Elimination of designated overhaul intervals offers great potential payoff in achieving significantly longer replacement times of helicopter drive system components.

b. The removal of a scheduled overhaul should result in a decrease or, at least, no increase in the number of failures that could possibly cause an accident.

c. If after installation, a component is removed prior to expiration of its scheduled TBO interval, it is essentially removed "on-condition."

d. The application of on-condition maintenance should be based on considerations of cost, mission effectiveness, and safety.

e. Components that contain only constant and/or decreasing hazard functions are excellent candidates for on-condition maintenance. On the other hand, components that contain increasing hazard functions are not as likely to be candidates for on-condition maintenance since there is an apparent advantage to be gained by overhauling the item and returning that item to a zero-time or like-new condition.

f. If a transmission lacks an inherent on-condition capability, i.e., exhibits an increasing hazard rate, test and field data should be analyzed to determine the correct TBO for that transmission from a mission effectiveness and cost standpoint.

g. With only minor modifications, the contractors who studied their particular aircraft drive trains each concluded that their respective components were suitable for on-condition maintenance.

h. Most of the failure modes that would affect a decision concerning whether or not to go to on-condition maintenance are currently known.

i. Those failure modes that are not detected by current diagnostic techniques and condition-monitoring devices exhibit a constant failure rate or hazard function.

j. The entire on-condition question really reduces to a safety issue. For those failure modes that do offer a potential safety problem and that exhibit increasing failure rates, the existing diagnostic and condition-monitoring devices and techniques are adequate to reduce those problems to mission or maintenance affecting rather than safety problems.

k. In the analysis of data to determine whether or not to institute on-condition maintenance, the two-parameter Weibull distribution was the most useful descriptor of failure data and it should be used to describe those failures.

l. The portion of a depot's workload that would be altered by going to an on-condition maintenance system entirely would be that portion due to components reaching their scheduled overhaul interval. Currently, about three-fourths of the drive system components removed are operating on-condition; i.e., they are removed and sent to a depot before the scheduled TBO.

m. Elimination of scheduled overhauls will decrease the current workload of the depots, but it is not true that the workload will not be steady. It should be if the drive system components' failure rate is constant. Similarly, an increasing hazard rate should result in an increasing workload and a decreasing rate in a decreasing workload. Bell Helicopter Company's drive system components exhibited a constant failure rate, whereas, the Boeing Vertol Company components exhibited a decreasing rate. Determination of how depot workload will be affected by going to on-condition maintenance will have to be assessed on a case-by-case basis.

n. The accumulated time on each life-limited part must be known to determine when that gearbox part will have to be replaced or the gearbox sent back to depot.

o. The increased forces imposed on uprated or new technology aircraft introduced into the fleet may affect the fatigue life to such an extent that wear phenomenona will not be displayed before fatigue failures occur.

p. Designation of certain Army aviation units to "lead the fleet," i.e., be 100 percent monitored, could be made to provide a controlled base for analytical teardown of the components being assessed. This would be done to provide data for TBO growth or on-condition maintenance justification. The data gathered would be used to define the hazard function for that component and hence, to decide whether to initiate a scheduled overhaul maintenance scheme or go to on-condition maintenance.

GENERAL CONCLUSIONS

The following conclusions are made by the authors based on the results of this analysis:

a. The ongoing TBO growth program can be greatly accelerated.

b. TBO assignment has little relationship to percent reaching the overhaul interval.

c. Data available indicates that safety-affecting failure modes are random; i.e., they display a constant hazard function, and having a scheduled overhaul interval would not eliminate those modes.

d. From the analyses contained in this report, it is apparent that should an emergency (such as a mid-intensity war) arise before on-condition maintenance were implemented, the current TBO intervals could be extended since the primary failure modes of the drive system components are not safety affecting. Instead, the modes encountered would be mission or maintenance affecting.

e. Diagnostics and condition-monitoring techniques and devices are needed to make on-condition maintenance a reality. However, extensive research to improve these techniques and devices will not contribute materially to whether or not on-condition

maintenance should be instituted. A note of caution is needed, however. If certain types of technology, e.g., gas bearings, were ever used in transmissions, it may become difficult to detect certain failure modes. Therefore, each new technology item introduced will have to be assessed to insure that any potential catastrophic failures can be detected prior to their occurrence.

f. On-condition maintenance should be considered for all future helicopter drive system maintenance programs.

g. TBO intervals for current drive system components of Army helicopters should be extended as quickly as possible, based on field data analyzed for relevant failure modes, until those intervals are sufficiently long to make those components in effect maintained on-condition.

RECOMMENDATIONS

CURRENTLY FIELDED AND FUTURE ARMY AIRCRAFT

The following recommendations are made based on the conclusions and analyses described in this report:

a. Extend the scheduled overhaul intervals of currently fielded Army helicopter drive system components as quickly as possible to that which would retire the components when their life limits (design or fatigue lives) are attained.

b. For future Army helicopters, designate certain Army aviation units as "lead-the fleet" units to gather data as a basis for determining whether to designate scheduled overhauls or go to on-condition maintenance. This entails obtaining sufficient data to determine the component's hazard function.

c. Use the two-parameter Weibull distribution to describe helicopter drive system hazard functions.

d. Extend designated overhaul intervals for future helicopter drive system components with constant and/or decreasing hazard functions until field data indicates that the overhaul interval can be eliminated.

e. For helicopter drive system components with increasing hazard functions, analyze test and field data from a mission effectiveness and cost standpoint to determine whether to maintain the item "on-condition" or to select an overhaul interval.

f. Continue to use existing diagnostics and condition-monitoring techniques and devices to minimize safety-related failure modes.

g. Continuously record time on any life-limited components to determine when those drive system components will have to be replaced or sent back to depot.

FURTHER STUDY

The following recommendations for further study are made based on the conclusions and analyses presented in this report:

a. An assessment must be made to determine how to provision and staff the depots should on-condition maintenance be instituted. This study is necessary since only components with decreasing or constant hazard functions would be returned to depot for overhaul or repair. For those components with a constant hazard function, provisioning and staffing would be fairly simple, but for decreasing hazard function components, the situation is no longer simple. The requirement for provisions and/or personnel to support components with decreasing hazard functions should be decreasing with time, depending

on the age distribution of the fleet. Correspondingly, it will be necessary to assess logically and precisely how the support function will change with time.

b. Since the current TBO system is used to incorporate modification work orders (MWOs) during a scheduled overhaul, a study should be made to determine how to incorporate those MWOs if on-condition maintenance were to become the accepted maintenance philosophy.

c. If on-condition maintenance were the accepted maintenance philosophy and a transmission contained life-limited parts, it might prove cost effective to allow field, i.e., Aviation Intermediate Maintenance level, replacement of those components. That issue must be studied for its impact potential and compatibility with the Army maintenance system.